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BOLIDE FRAGMENTATION PROCESSES: SINGLE-BODY MODELING VERSUS THE CATASTROPHIC FRAGMENTATION LIMIT

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ABSTRACT

The catastrophic "pancake" fragmentation process, proposed as being generally applicable to very large meteoroid entry in the early 1990's by a number of workers, has been carefully examined. In this effort, the transition from the traditional single-body dynamics and energetics model to a catastrophic "pancake" fragmentation process has been delineated. The key parameters are the μ parameter originally proposed by Levin and the fragmentation scale height, H_f, which we have derived from μ. It has been found that this break-up process can only occur for an optimum set of circumstances.

1. INTRODUCTION AND OVERVIEW:

1.1 Simple ablation theory: A brief summary

Following Bronshten (1983) and ReVelle (1999), we have initially assumed that an analytic solution for hypersonic meteoroid entry, assuming a hydrostatic, isothermal, atmosphere with a constant ablation coefficient, σ and a height variable velocity, while allowing for shape change using a constant μ parameter value is adequate to investigate this problem. Additional assumptions associated with this solution of simultaneously including ablation, deceleration, shape change and also the process of catastrophic fragmentation (as defined here) is the neglect of lift, coriolis effects and gravity gradients, non-isothermal and non-steady atmospheric effects, etc. Two fundamental regimes have been identified, namely:

i) **$| H_p / H_f | << 1$:**
Single-body model approximation

H_f = fragmentation scale height
H_p = pressure scale height

Previous investigators have also identified the following behavior within this limit:

a. $\mu \equiv 2/3$: Self-similar ablation regime with no shape change.
b. For $0 \le \mu < 2/3$: Ablation and deceleration, while allowing for simultaneous shape change
c. A(z) decreasing with decreasing height with $| H_p / H_f | << 1$

ii) **If $H_p / H_f >> 1$:**
Catastrophic "pancake" fragmentation

For $\mu < 0$, there is the possibility of simultaneous ablation and deceleration, while allowing shape change, but with A(z) increasing with decreasing height

It is this latter regime and the transition from the realm of applicability of the single-body approximation that we want to outline in this paper. Independently ReVelle and Ceplecha (2001f) have evaluated the most precise bolide flight data available for sizes up to ~ 1m across and have found very little support for the process of catastrophic fragmentation.

2. PREVIOUS MODERN FRAGMENTATION MODELING

2.1 Break-up schemes: Uniform and porous limits

Various schemes have been proposed by different workers regarding the drag area and heat transfer areas during entry. In the single-body limit these areas are equal:

A_d (drag) = A_h (heat transfer)

if the bodies are homogeneous (uniform in bulk density). For porous bodies, ReVelle (1983, 2001a) has shown that:

$$\mathbf{A_h = A_d \cdot (1+\psi')^{-1}}$$

where

ψ' = normalized porosity function ($0 < \psi' < 1$)

which is assumed to be zero (or very small compared to unity) in the ordinary chondrite limit (bolide type I.).

2.2 Specific types of approaches for modeling fragmentation:

a. Increase of the frontal cross-sectional drag area proportional to the number of fragments produced during fragmentation.
b. $A_h >> A_d$ due to turbulent mixing of air/ablated vapor
c. Significant porosity effects: $A_h >> A_d$
d. Progressive fragmentation processes producing a cascade of break-ups starting after the initial triggering process.
e. "Pancake" break-up without ablation: Rapid lateral growth of the body
f. "Pancake" break-up with ablation included

Most of the recent "pancake" efforts on this subject have been associated with the dramatic entry into Jupiter's atmosphere of Comet Shoemaker-Levy 9, i.e., for very large bodies (hundreds of meters to kilometers across). These pancake models were never expected to work for objects as small as the typical US DoD bolides or for the still smaller bodies photographed by ground-based camera networks (personal communication with J.G. Hills, 2001). In the forthcoming **Icarus** paper a full summary will be given of all of these process types along with the credits due to the authors of these numerous contributions on the fragmentation process.

2. 3 Possible break-up mechanisms:

The standard break-up mechanisms that have been previously proposed include both thermal and mechanical forcing. The thermal mechanism has been shown to be very unlikely except perhaps for Nickel-iron bodies with very large thermal conductivity. This process is much too inefficient a process because of the long time-scales that are necessary for it to be effective. In this paper we assume that the later mechanism is operative once a triggering has been established. We assume that mechanical effects dominate the break-up process and that pressure loading on the front al cross-section leads to a "triggering" of break-up if the stagnation pressure ≥ uni-axial tensile/compressive strength of the body. We also assume that any earlier break-up (before this triggering by pressure loading is reached) is due entirely to internal weaknesses in the body, such as fracture planes, from cracks produced during prior space collisions.

An additional mechanism described in ReVelle (1980) suggested that the very rapid shape change process initiated by the large ablation rate at the stagnation point could aid in triggering fragmentation. The gradient in the ablation rate at the stagnation point compared to radial positions far removed from the stagnation point was suggested as a mechanism for allowing additional weaknesses in the integrity of the body to develop so that break-up would be more likely.

3. BOLIDE FRAGMENTATION PROCESSES AND THEIR IMPLICATIONS

3.1 Single-body model limit:

$$\mathbf{|H_f| >> H_p}$$

where

The fragmentation scale height, H_f

$H_f = -f(z)/\partial f/\partial z$; $f \equiv A(z)/A_\infty$

H_f = the vertical distance (downward) by which the instantaneous cross-sectional area, A(z), increases by 1/e.

The pressure scale height, H_p is defined as:
$H_p = -p(z)/\partial p(z)/\partial z = RT/g$ (if hydrostatic):
$H_p \sim$ 6-8 km from $0 \leq z \leq 120$ km

The full details of all of the concepts and derivations in this paper along with the fundamental single-body and post fragmentation diagnostic indicators regarding a bolide entry trajectory will be submitted to **Icarus** during early 2002. Because of primarily space limitations, only a limited selection of results will be provided here.

Prior to the onset of fragmentation, we assume that only smooth, quasi-continuous break-up processes are occurring. This has been the case used prior to the early 1990's for almost all workers for bolide and meteor modeling efforts. In this regime, ablation, deceleration and quasi-continuous fragmentation all occur simultaneously as the body size decreases at various rates determined by the ablation coefficient and by the changes in the bolide velocity during entry.

3.2 Catastrophic "pancake" fragmentation:

$$\mathbf{H_f << H_p}$$

or:

$$\mathbf{H_p / H_f >> 1}$$

In this regime of flight , $\mu < 0$ and the frontal cross-sectional area of the body increases with decreasing height. In this development, $\mu < 0$, is a necessary condition for the rapid lateral growth of the body, but for the effect to be dynamically or energetically significant, a sufficient condition must also be satisfied, namely that the ratio: $H_p / H_f >> 1$. We have assumed that a sudden onset of catastrophic fragmentation occurs by the triggering process when the stagnation pressure exceeds the strength of the body. We have not yet completed the analysis of $\mu < 0$ on the emission of light, but only on the dynamics of entry, but we will present evidence below that the same parameters control the light emission process for this break-up limit. In addition there is also an expression originally due to Levin (1962) for the model of light emission presented in Bronshten (1983), including the case $\mu < 0$, but this expression was devised for the limit in which$\{\sigma, V, \mu\}$ = constant. This is the standard meteor light curve developed by assuming proportionality to the mass loss rate. In the **Icarus** paper a full derivation for the case where the first two of these quantities are height variable will be presented. Also, an expression for the light curve that was derived by assuming light emission is proportional to the time rate of change of the kinetic energy will be presented as well. These assumptions are clearly more applicable to the large bolide case.

3.3 Scale height ratio implications

3.3.1 General Implications

As a result of our evaluation of the scale height ratio, H_p / H_f, that will be presented in full detail in **Icarus**, for $\mu < 0$, we can say that in both the negligible and large deceleration limit this scale height ratio increases. Similarly, this is also the case for larger σ, for larger $\sigma V^2(z)$, for larger μ (< 0) and for larger initial velocities (for large decelerations). Also, this scale height ratio increases for a smaller initial radius, for smaller radii at lower heights, for smaller bulk density (using a uniform bulk density model) or for a smaller entry angle, θ. In the limit of no ablation, the scale height ratio $\rightarrow 0$ as $\sigma \rightarrow 0$. The scale height ratio also $\rightarrow 0$ as $\mu \rightarrow 0$. Thus, severe ablation or large μ (< 0) promotes catastrophic break-up as the body size decreases with decreasing height. Such behavior is not bounded however. If $\mu = -3.33$, a frontal area increase of 500-1000 times and much higher end heights are predicted. Thus, from our analysis, we have found that bolides with an optimum σ or large μ (at higher altitudes) or with larger initial speeds are likely to break-up catastrophically as a result. Similarly, If σ is too large, the end height velocity will be quite large and μ will be not < 0 and catastrophic break-up is less likely to occur, since the definition of the onset of fragmentation will not been satisfied.

3.3. 2. Scale height ratio for the same initial velocity, σ, θ, etc.

Effects of e-folding energetics using the D parameter of ReVelle (1993). For D = 2.30 ($\rightarrow$10 % kinetic energy reduction), smaller decelerations are expected which are more generally consistent with the behavior of bolides of cometary origin. The end height velocity is also larger which makes the largest possible μ

value less negative. Thus, catastrophic break-up is far less likely to occur, for this case. For D = 4.61 ($\rightarrow$1 % kinetic energy reduction), larger decelerations are expected, which are more generally consistent with meteorite-dropping fireballs. The end height velocity is also far smaller which makes the largest possible μ value more negative. Thus, catastrophic break-up is far more likely to occur for this case.
Both of these limiting D values also have a nearly linear increase of H_p / H_f as height decreases, except for progressively smaller μ's. The increase in frontal area for $\mu < 0$ produces more atmospheric drag and a progressively higher end height. Thus, μ can not become too large otherwise the end height will rapidly increase as the frontal cross-section rapidly increases.

3.3.3 Implications for Break-up

If the stagnation pressure loading on the frontal cross-section is the fundamental mechanism for break-up, with all other factors the same, direct analysis of the fundamental equations shows that larger bodies will only break-up catastrophically ($\mu < 0$) if they are extremely strong. Conversely, smaller bodies will only break-up catastrophically ($\mu < 0$) if they are extremely weak. Thus, for a necessarily limiting range of body strengths, an optimum size or mass range exists where catastrophic type, "pancake" break-up will occur, corresponding to $\mu < 0$. Otherwise, for $\mu > 0$, only quasi-continuous fragmentation processes can occur under these assumptions.

4. FRAGMENTATION AND LIGHT EMISSION

4.1 Previous analytical studies of the effects of fragmentation on light emission

In Bronshten (1983) an analytical expression, originally due to Levin (1962), for the effects of μ on the emission of light is presented, namely:

$$\mathbf{I \equiv dm/dt/(dm/dt)|_{max}}$$

$$\mathbf{I = I_{max} \cdot \{\mu^{-\mu/(1-\mu)}\} \cdot \{\rho(z)/\rho_{max}\} \cdot [1-(1-\mu) \cdot \{\rho(z)/\rho_{max}\}]^{\mu/(1-\mu)}}$$

where

I = Assumed isotropic light emission in Joules/s
ρ_{max} = air density at the altitude of maximum light emission

$$\mathbf{\mu \equiv \{\ln (A(z)/A_\infty)/\ln(m(z)/m_\infty)\}}$$

or:

$$\mathbf{A(z) \equiv A_\infty \{m(z)/m_\infty\}^\mu}$$

where the subscript ∞ refers to values at the top of the atmosphere (initial values) and m is the instantaneous mass of the bolide and A(z) is the bolide frontal cross-sectional area.

The light emission formula was derived from classical meteor theory for an isothermal, hydrostatic atmosphere, assuming that $\{V, \sigma, \mu\}$ were all constants. Its range of applicability should be quite small for large bright bolides where air drag (and consequently very large deceleration) is very significant. Also, for very large negative μ, drag is even more important and the formula is even less likely to be very useful. Such large negative μ values have the desirable property of increasing the end height of bolides quite dramatically, but to achieve the necessary increase in the end height to explain the bolide behavior for groups IIIA or IIIB, the frontal cross-section of the body must increase > 500 times! This is clearly a very unrealistic possibility. In addition, the general expression of Levin reproduced above produced results, which have an imaginary component below the altitude of maximum light emission for large bodies. Clearly, although of interest because of its dependency on μ, we should develop alternative expressions for the effects of fragmentation on the light emission process.

4.2 The fragmentation scale height for light emission: The height of maximum light

In order to illustrate the influence of these limiting parameter regimes, we now evaluate the altitude of maximum light emission in an approximate manner. We start from the assumed balance between the light output and the product of the luminous efficiency and the time rate of change of the kinetic energy. The first derivative is then taken and equated it to zero to find the altitude of maximum light emission for a uniform bulk density meteoroid. Slight changes are required for this expression for a porous meteoroid model, as will be summarized below:

$$\mathbf{dI/dt = d/dt\ \{-\tau \cdot dE_k\ /dt\}}$$

where

$$\mathbf{dE_k\ /dt = -(V^2/2)\cdot dmdt \cong -0.25\rho \cdot V^5 \cdot C_D \cdot \sigma \cdot A}$$

which has been evaluated for $2/(\sigma \cdot V^2) << 1$ (small deceleration limit) with an unchanging body shape and for simplicity with τ , σ, V, and C_D = all constant, where C_D is the drag coefficient for hypersonic flow:

$$\mathbf{d/dt\{dE_k\ /dt) = -0.25(\tau \cdot \sigma\ C_D\ )\cdot d/dt\{\rho \cdot\ V^5 \cdot A\} = 0}$$

which can be simplified further to a height derivative form using the ancillary relations:

$$\mathbf{dz/dt\ = -V(z)\cdot \sin\theta}$$

$$\mathbf{A\ = A_\infty \cdot \exp[\sigma \cdot (\mu-1)\cdot\ (V_\infty{}^2-V^2(z))]}$$

Letting:

$A = A_d$ = frontal drag area

to the form:

$$\mathbf{\sin\theta \cdot \{-(1/\rho)\cdot \partial\rho\ /\partial z-(1/A_d)\cdot(\partial A_d/\partial z)\} = (5/2)\cdot\{\rho(z)\ A_d \cdot C_D/m\}}$$

In an isothermal hydrostatic atmosphere, we also have the results:

where

$$\mathbf{1/H_p = -(1/p(z))\cdot(\partial p(z)/\partial z)}$$

$$\mathbf{1/H_\rho = -(1/\rho(z))\cdot(\partial\rho(z)/\partial z)}$$

$$\mathbf{\rho(z) = \rho_o \cdot \exp[-z/H_p]}$$

$$\mathbf{p(z) = p_o \cdot \exp[-z/H_\rho]}$$

H_p = RT/g = constant for an ideal gas
H_ρ = density scale height
$H_\rho = H_p$ (only if isothermal conditions exits)
p_o = atmospheric pressure at the surface (z = 0)
ρ_o = atmospheric density at the surface (z = 0)

and similarly:

$$\mathbf{1/\ H_f(z) = -(1/A_d(z))\cdot(\partial A_d(z)/\partial z)}$$

Turning to pressure as the atmospheric variable and making use of the ideal gas law, we can then solve for z at maximum light. Thus, we have arrived at the following general expression:

$$\mathbf{z_{max} = -\ H_p \cdot\ \ln\{0.40\cdot\{p^*(z)\ /p_o\ \}[H_p\ /H_f(z)+ 1]\}}$$

where

$p^*(z)$ = modified ballistic entry parameter
" $\equiv mg\sin\theta/(C_D \cdot A_d)$
m = instantaneous bolide mass
g = acceleration due to gravity

$$\mathbf{p^*(z) = p^*_\infty \cdot\ \exp[(\sigma\ /2)(\mu-1)\cdot\ (V_\infty{}^2-V^2(z))]}$$

p^*_∞ = initial modified ballistic entry parameter

which for single-body behavior ($H_p /H_f(z) << 1$) reduces to:

$$\mathbf{z_{max} = -\ H_p \cdot\ \ln\{(0.40)\{p^*(z)\ /p_o\}\}}$$

while for catastrophic fragmentation ($H_p /H_f >> 1$), this expression becomes:

$$\mathbf{z_{max} = -\ H_p \cdot\ \ln\{(0.40)\{p^*(z)\ /p_o\}[H_p\ /H_f(z)]\}}$$

The large increase in the height of maximum light for the limiting case in which catastrophic fragmentation dominates the light emission behavior is clearly evident from the latter expression. This is the case since the quantity inside the natural logarithm is so greatly increased by virtue of the small fragmentation scale height. This is directly due to the large increase in the drag that is experienced by a laterally expanding object traveling at a hypersonic velocity.

The expression for the fragmentation scale height can be further modified if a porous meteoroid model is adopted so that $A_h \neq A_d$. In this case the definition of H_f in the expressions above becomes:

$$\mathbf{H_f(z) = -f(z)/\partial f(z)/\partial z;\ f(z) \equiv A_h(z)/A_{h\infty}}$$

or

$$\mathbf{H_f(z) = -(1/A_h(z))\cdot(\partial A_h(z)/\partial z)}$$

i.e., now specifically written in terms of the heat transfer area and with all other terms remaining the same as before. This is very significant since for very porous objects the heat transfer area can increase dramatically compared to the definition of H_f in terms of A_d for the uniform density case for objects with negligibly small porosity (such as Group I., etc.).

4. SUMMARY AND CONCLUSIONS

A newly discovered concept, the fragmentation scale height, H_f (z) needs to be compared against the local pressure scale height, H_p (z) in order to determine if a single-body approach or a catastrophic fragmentation type approach is evident for a specific problem. We have indicated that if: $H_f(z) >> H_p(z)$, the single-body approximation is valid, whereas if $H_f(z) << H_p(z)$, catastrophic type "pancake" fragmentation is expected.

We have also independently evaluated these parameters using data from the most precise bolide trajectories that are available (ReVelle and Ceplecha, 2001f). From this work we have independently determined that catastrophic fragmentation behavior is not very likely to occur for most bolides.

Assuming that μ is $\neq$ f(body size) and not too negative ($|\mu| < \sim 3.33$), the start of "pancake" fragmentation occurs for lower density bolides of high initial speed, at shallower entry angles and having a larger ablation coefficient. Larger (smaller) bodies can only break-up by this mechanism if they are exceptionally strong (weak). Thus, there is an optimum range of masses for which this can occur (if μ = constant). Unfortunately, μ , is also far from constant as shown by ReVelle and Ceplecha (2001f). Direct observations of the most precise bolides by ReVelle and Ceplecha (2001f) also does not show much support for a catastrophic type break-up process for bodies as large as ~ 1 m across. Only 8 of 22 observed bolides exhibited significantly negative μ values. Even fewer cases showed that $H_f << H_p$ over any height region. Thus, many bolides (including the frequently observed bolides recorded on US DoD satellite sensors) can be safely treated using the single-body theory with $\mu > 0$. Pancake type break-up is generally not expected to occur.

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